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FINAL REPORT

ADVANCED HIGH FREQUENCY PARTIAL DISCHARGE MEASURING SYSTEM

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(NASA-CR-195240) ADVANCED HIGH FREQUENCY PARTIAL DISCHARGE MEASURING SYSTEM Final Report (Arizona State Univ.) 31 p

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1. Introduction

This report explains the Advanced Partial Discharge Measuring System in ASUs High Voltage Laboratory and presents some of the results obtained using the setup. While in operation an insulation is subjected to wide ranging temperature and voltage stresses. Hence, it is necessary to study the effect of temperature on the behavior of partial discharges in an insulation. The setup described in this report can be used to test samples at temperatures ranging from -50°C to 200°C (-58°F to 392°F). The aim of conducting the tests described herein is to be able to predict the behavior of an insulation under different operating conditions in addition to being able to predict the possibility of failure.

1.1 History

Dielectrics subjected to high voltage and high temperatures undergo stresses which cause them to deteriorate with time and eventually fail. This deterioration is initiated due to partial discharges (PD) in the gas filled voids or cavities contained within the dielectric. These voids are inherent to the process used in the manufacturing of these dielectrics and depending on their quantity, size and shape, the destructive effect of the partial discharges differ. The air leaking into the mould during curing may form a void, or insufficient pressure on the liquid epoxy during curing may permit gaseous cavity to develop due to the vapor pressure of an epoxy component. In addition, foreign particles such as dirt, paper, textile fibers, etc. , in the dielectric may lead to void formation.

The permitivity of the medium in a cavity is usually lower than that of a solid insulation and this causes the field intensity in the cavity to be higher than that in the dielectric. Hence, for such an insulation even under normal working stress, the voltage across the cavity may exceed the breakdown value and initiate a breakdown in the void.

Every discharge event degrades the material due to the energy impact of high energy electrons or accelerated ions. In addition, these impacts may also cause chemical transformations of many types.

The detection of these partial discharges is based on energy exchanges which take place during the discharge. These exchanges manifest themselves in the form of electrical impulses, dielectric losses, electromagnetic radiation, sound, increased gas pressure, heat and chemical reactions. Thus discharge detection and measurement techniques can be based on the observation of any of these parameters.

Over the years many measuring techniques have been devised beginning with the simplest and oldest "hissing test" where the noise produced by the discharges indicates their presence, to the latest very sophisticated digital instrumentation.

Partial discharge measuring systems can be classified as non electrical and electrical based on the physical parameter associated with the measurement of the discharges. Non- electrical systems measure energy exchange in the form of chemical transformations, gas pressure, heat, sound and light. However, electrical methods are used more frequently. These methods aim to separate the impulse currents linked with partial discharges from any other phenomena. The impulse current is then used to analyze the partial discharge activity in the device under test.

The four steps needed for a complete correlation of partial discharges with their degrading effect on insulating materials are : detection, measurement, location and evaluation. Detection refers to the certainty that discharges are present in the sample under test. After a discharge pulse has been detected, its magnitude is determined in the measurement stage. For some apparatus like power transformers and high voltage cables, it is important to locate the precise source of partial discharges. This however is not the case when testing small devices like capacitors with capacitances of the order of microfarads for which, the sensing of partial discharges is more important than pinpointing the partial discharge site. The final step, evaluation, allows an estimation of the type of danger that the detected discharges represent to the insulation being tested and, the information thus obtained is used to predict the useful life of the sample under specific operating conditions.

1.2 Problem

Current research and development efforts to improve the ability of the electrical insulation systems to withstand energy discharges are heavily dependent on partial discharge diagnostic systems that can provide accurate and meaningful test data.

The primary purposes of partial discharge analysis in research and development are to :

- Correlate the partial discharge behavior exhibited by the dielectric material under different test conditions.

- Try to provide a basis for predicting the probability of failure of a dielectric based on the partial discharge behavior.

- Predict an optimum operating temperature for a dielectric with a view to minimize partial discharges and aging.

A detailed analysis of partial discharges is required because dielectrics under high stress conditions deteriorate due to the effect of microdischarges taking place in gas-filled voids or cavities. The deterioration varies with the number of discharges and in turn the number of discharges vary with increasing electrical stresses.

Also in the design of modern electrical and electronic systems there is a tendency to further stress the dielectric materials like for example by increasing the operating voltage and frequency to reduce the weight and physical size of electrical equipment in aerospace applications. This calls for more stringent testing for partial discharges in order to ensure high levels of reliability.

It is necessary to simulate the wide range of temperatures to which the dielectric may be subjected while in operation. Also, the need is felt for a real time computer-based data acquisition system able to perform partial discharge analysis and storage of pulse data for subsequent statistical analysis.

1.3 Purpose

The purpose of this research is to setup a partial discharge measurement and analysis system which can be used to conduct tests over a wide range of operating temperatures.

The setup developed in ASUs High Voltage Laboratory can be used to monitor and record the partial discharges occuring within a dielectric. The sample can be mounted within the temperature chamber and the partial discharges monitored to determine the corona inception voltage over the full temperature range. Also, the real time data acquisition and analysis system can be used to study the aging of the dielectric due to temperature cycling and electrical stresses. In addition a statistical analysis of the data can be obtained.

2. Description of the system

The setup presented in this report enables the study of partial discharges in samples over a wide range of temperatures and also facilitates monitoring of the aging in the sample.

The partial discharge measuring system consists of following :

a) High Voltage Source
b) Temperature Chamber
c) Partial Discharge Detection System

d) Data Acquisition and Analysis System

e) Partial Discharge Monitoring System

- Tektronix 2430A Digital Storage Oscilloscope
- Haefely PD561 Partial Discharge Detector

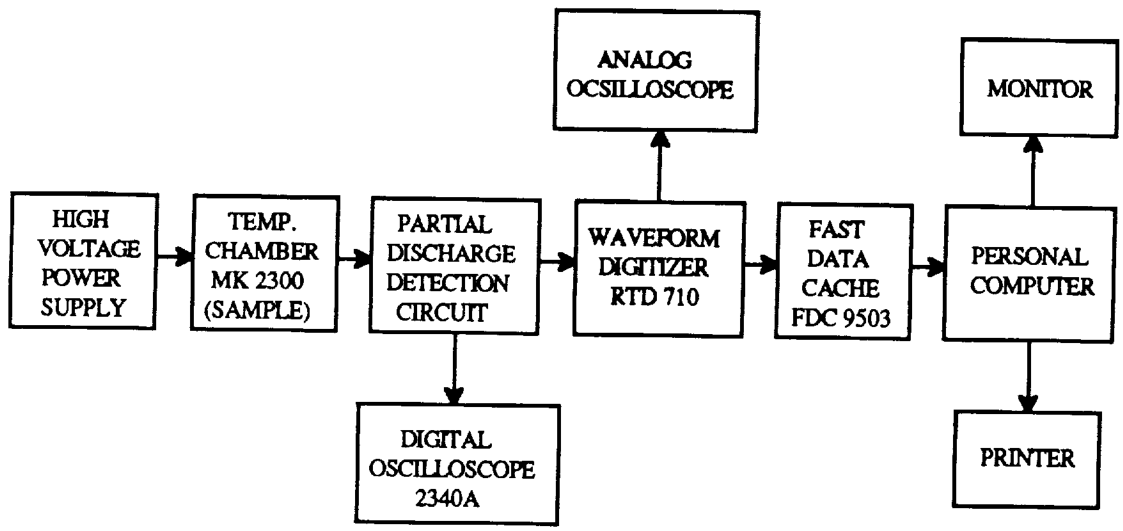

Fig 1. GENERAL BLOCK DIAGRAM OF THE PARTIAL DISCHARGE MEASURING SYSTEM

2.1 High Voltage Source

The high voltage source used for the partial discharge measurement system is a 7200 - 120 V, 0.8 KVA potential transformer. The secondary voltage of the potential transformer can be varied from 0 V to 7200 V by varying the primary voltage using a 120V, 1.8KVA autotransformer. The autotransformer is fed through an EMI/RFI suppression filter and a ground fault circuit interrupter.

The high voltage bushing of the potential transformer is connected to the partial discharge detection network through a 100Ω, 175W wirewound ceramic resistor, to limit the secondary current in case of test sample breakdown. All these connections are made using high voltage silicone rubber cable which is extremely flexible and designed to have high corona inception voltage compared to other cables. A semiconductive strand shield of silicone rubber effectively eliminates corona that otherwise forms in the air layer between the stranded conductor and insulation in other types of cables.The entire setup was found to be discharge free over the entire temperature range at test voltages below 3.6 KV.

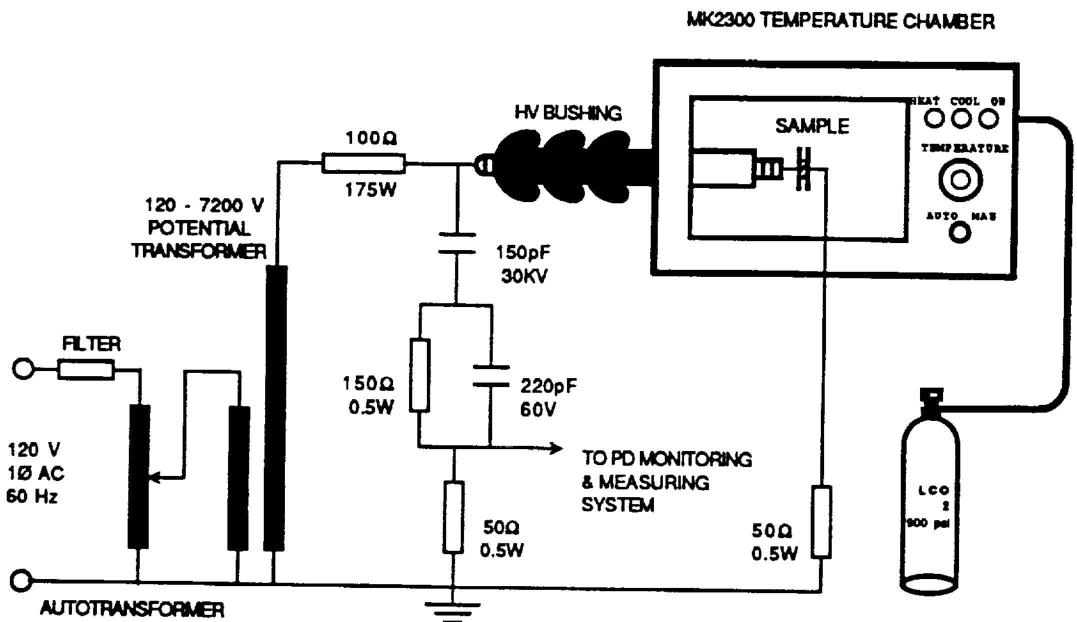

Fig 2. ONE LINE DIAGRAM SHOWING THE HIGH VOLTAGE SOURCE, PARTIAL DISCHARGE DETECTION SYSTEM AND THE TEMPERATURE CHAMBER

2.2 Temperature Chamber

This is a Delta Design MK2300 temperature chamber which is rated at 1520 Watts and operates off 120V, 60Hz single phase a.c. supply. The chamber uses Liquid Carbon Dioxide (LCO_2) at 900psi for cooling and has dual twenty ohm nichrome wire elements to give a total of 1440 Watts of heating power. The chamber can be operated over a temperature range of -50°C to 200°C with an accuracy of ±5°C . A 140CFM centrifugal blower with baffling provides equal distribution throughout the chamber in a vertical air flow pattern.

The cool down takes approximately 5 minutes, from ambient to -50°C and 20 minutes from ambient to 200°C. When used in the automatic mode the chamber maintains the temperature at the set value by automatically switching between heating and cooling modes.

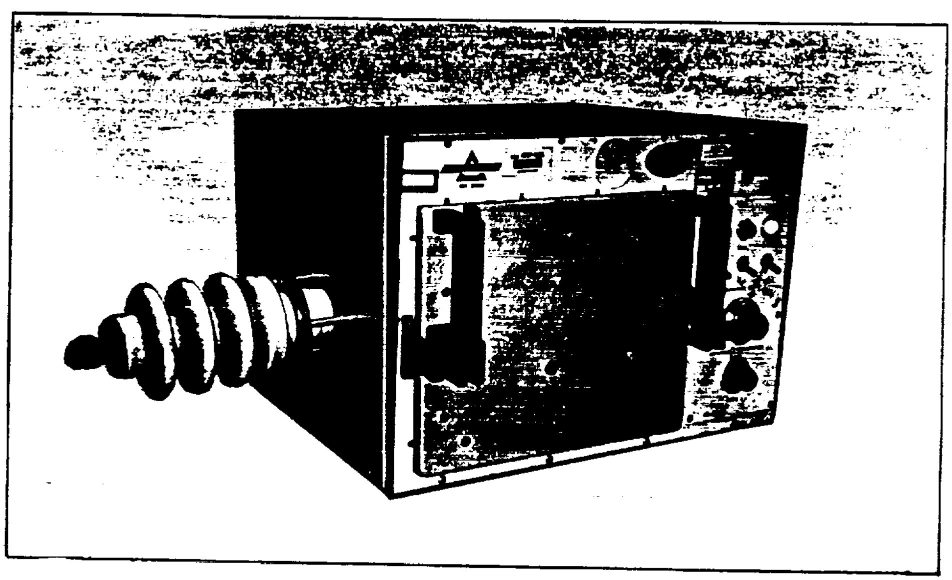

Fig 3. TEMPERATURE CHAMBER

An 80TK Fluke thermocouple module alongwith a Fluke digital multimeter is used to monitor the temperature continuously. The 80TK thermocouple module accepts the output of any K-type thermocouple and converts it to a 1 millivolt per degree (Celsius or Fahrenheit). The multimeter displays the temperature directly in degrees Fahrenheit or Celsius when set to the 200, 300 or 400 mV d.c. range.

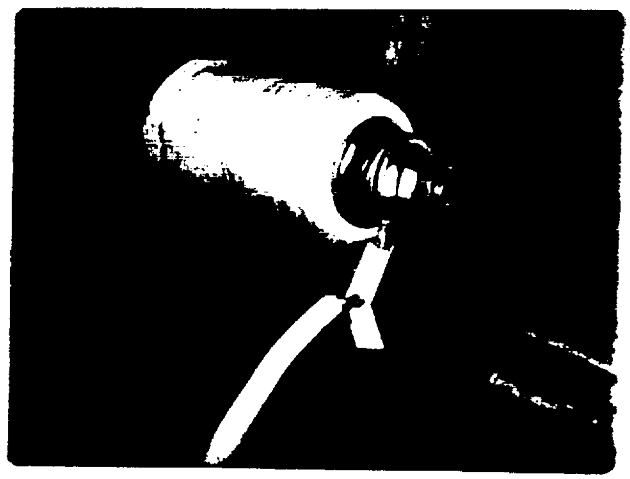

Fig 4. SAMPLE MOUNTING WITHIN THE CHAMBER

A 15KV class, 110KV BIL distribution transformer bushing has been mounted on the side wall of the temperature chamber in order to feed the high voltage to the sample mounted within the temperature chamber. The return path from the chamber is a high voltage silicone rubber cable rated at 15KVAC and having a capacitance of 65pF/ft (at 1KHz, 100% shield by water immersion). The insulation resistance of the cable is > 10^4 MΩ/1000ft (at 500VDC, one minute, 100% shield by water immersion at room temperature) and the operating temperature range is -65°C to 200°C . The temperature chamber is well grounded thus completely shielding the sample under test from external noise and interference.

2.3 Partial Discharge Detection System

This is a very sensitive detection system used to detect discharges within dielectric samples.

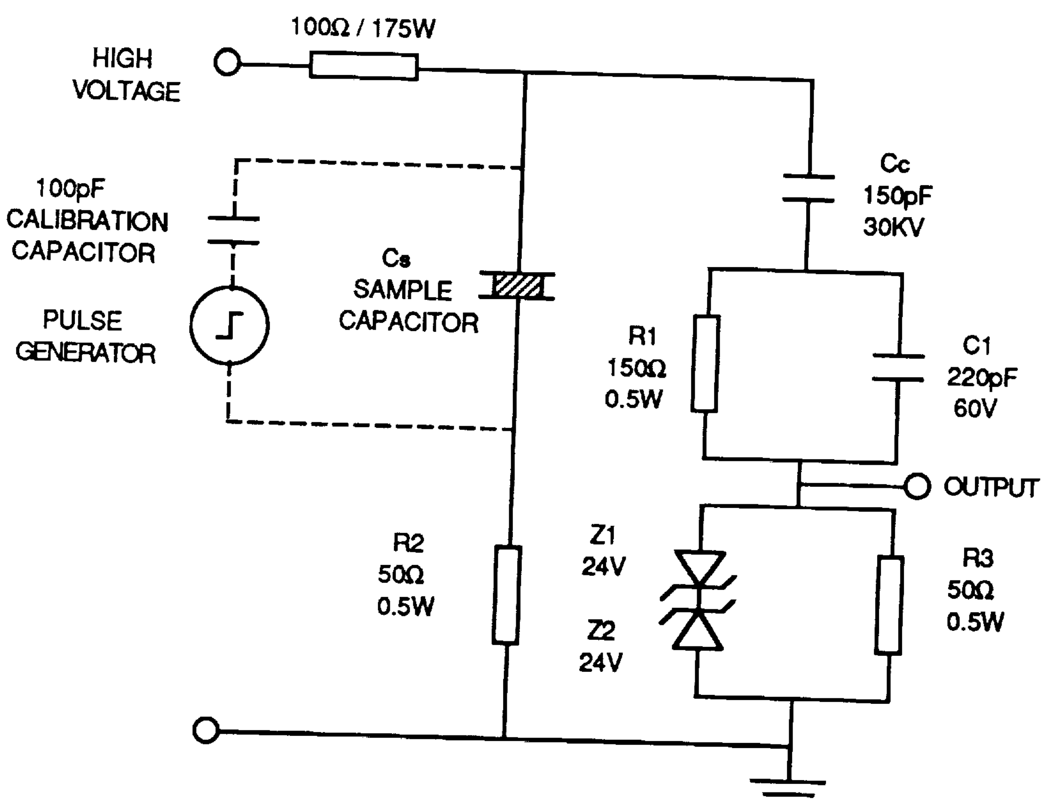

Fig 5. SCHEMATIC OF PARTIAL DISCHARGE DETECTION CIRCUIT SHOWING THE CALIBRATION

The detection system uses a 150pF / 30KV vacuum capacitor for coupling and a 150Ω, 0.5W carbon film resistor in parallel with a 220pF, 60V mica capacitor for compensating the stray inductances in the detection circuit. The other components are a 50Ω, 0.5W carbon film resistor between the sample capacitor and ground, and a 50Ω, 0.5W carbon film resistor used as a detection impedance.

The PD detection system was calibrated using a Wavetek 147HF Sweep Generator. A square wave pulse with less than 0.1usec rise time was fed through a 100pF calibration capacitor, across the sample capacitor and the output pulse across the 50Ω detection impedance observed using the Tektronix 2430 Digital Storage Oscilloscope. As expected the output waveform was observed to have a fast risetime and a long decay time.

2.4 Data Acquisition and Analysis System

The Data Acquisition and Analysis System being used at ASU uses a pulse-processing approach which provides the following features:

- A Real Time Acquisition system that increases the number of pulses processed per unit time.
- Long duration recording of bursts of Partial Discharges in a sample.
- Ability to store data points of several waveforms from the same sample for further analysis.

The Data Acquisition and Analysis System consists of the following equipments:

- Sony/Tektronix RTD 710 Real Time Waveform Digitizer
- Tektronix FDC 9503 Fast Data Cache
- Personal Computer (with ASUPD Software Ver 1.6)

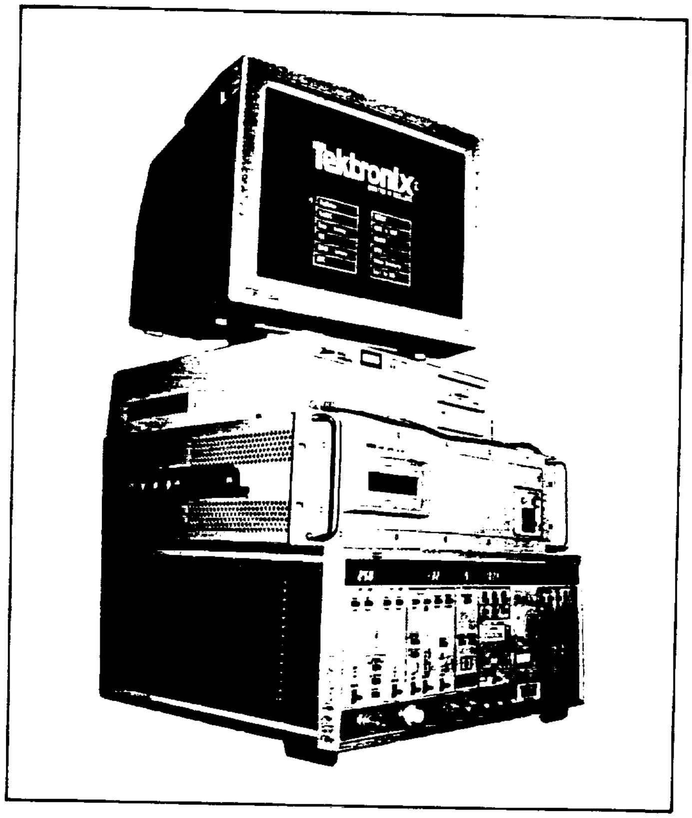

Fig 6. DATA ACQUISITION AND ANALYSIS SYSTEM

The equipments of the data acquisition system communicate over the GPIB interface bus. The Sony/Tektronix RTD 710 is a fully programmable real time waveform digitizer and is used at the maximum sampling rate of 200MHz. The output pules from the partial discharge detection system are fed to channel 1 of the digitizer. When the amplitude of an incoming pulse reaches the selected trigger level, a trigger pulse is generated and the sampling process starts. The digitizer records all the data points of a memory record, and holds until a new trigger pulse is generated to restart acquisition. The RTD 710 working by itself can send through the GPIB bus a maximum of 64 records once its internal memory has been filled. In order to increase this capacity and store data at the same speed as it is digitized the Fast Data Cache (FDC) 9503 is used as an external memory unit.

The FDC 9503 can store upto 16 Megawords per channel and when used in the "interleave mode" in conjunction with the RTD 710 can record data at a rate of 200 Megasamples per second.

The FDC 9503 then transmits the data over the GPIB interface bus to the personal computer where the ASUPD software analyses the data and prints out log reports on a dot matrix printer. The ASUPD software can either be used in the automatic mode or manual mode. When used in the automatic mode the computer automatically arms the digitizer in order to obtain data at fixed intervals of time set by the user and, subsequently prints out log reports. On the other hand, in the manual mode the user has to manually invoke the ASUPD software each time the data needs to be obtained.

2.5 Partial Discharge Monitoring System

The Partial Discharge Monitoring System has been incorporated to enable the visual monitoring of the partial discharge pulses produced in the sample. The two equipments used for this purpose are:

- Tektronix 2430A Digital Storage Oscilloscope and

- Haefely PD561 Partial Discharge Detector

The following information about partial discharges can be obtained using these equipments:

- Peak amplitude of partial discharge pulses.
- Frequency of discharges
- Waveshape of discharges at the output of Partial Discharge Detection System.
- Average charge of partial discharges in pC or nC.

3. Test Protocol

This section describes the steps to be followed and the aspects to be considered while running tests using the partial discharge measurement system. Basically, there are two kinds of measurements and analysis performed to study the partial discharges and they are as follows:

- Detection of partial discharge initiation voltage as a function of temperature.
- Monitoring of the aging caused by partial discharges.

3.1 Partial Discharge Initiation Voltage as a function of Temperature

While in operation an insulation is subjected to large variations in temperature and voltage. Hence, for reliable performance of the insulation it is necessary to study the effect of temperature on the partial discharge initiation voltage. Only on the basis of this can the safe operating range of the insulation be predicted. This test also gives an indication of the way the sample would behave when subjected to conditions beyond the range it has been designed for.

This test uses the setup shown in fig 2. and the partial discharges can be "monitored" using the Tektronix 2430A digital oscilloscope or the Haefely PD 561 partial discharge detector. The protocol to be followed is as follows:

1. The equipments should be setup as shown in the block diagram in fig 7.

2. If the Haefely partial discharge detector PD 561 is used in conjunction with the passive coupling quadripole CQ565 for monitoring, the calibration procedure outlined in the manual should be followed using the 100pF low voltage calibration capacitor and the built in calibrator.

3. Alternatively if the Tektronix 2430A digital oscilloscope is to be used, the output of the partial discharge detection system should be fed to channel 1 (CH1) and the CH1 coupling should be set to DC with 50Ω internal termination and the vertical gain should be set to 2mV/div. The horizontal time base should be set to around 200ns/div.

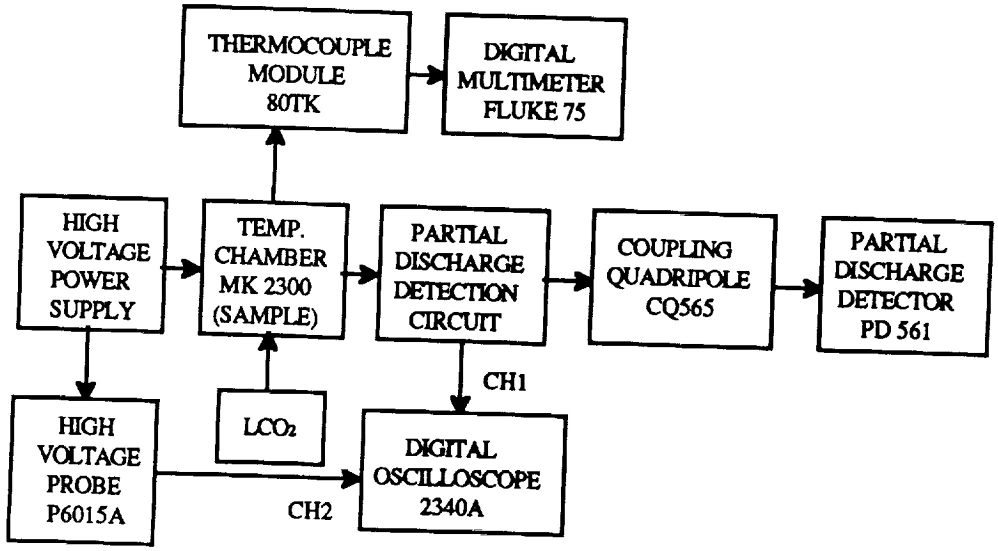

Fig 7. BLOCK DIAGRAM OF THE SETUP FOR THE STUDY OF THE EFFECT OF TEMPERATURE ON THE PARTIAL DISCHARGE INITIATION VOLTAGE

4. The high voltage applied to the sample is measured using the Tektronix P6015A high voltage probe. Hence, the output of this probe which is scaled down by a factor of 1000 has to be fed to CH2 of the digital oscilloscope.

5. Making sure that the power to the potential transformer has been switched off and the HV bushing of the potential transformer has been grounded, the sample to be tested has to be mounted in the temperature chamber.

6. Before closing the front door of the chamber it is necessary to check that the thermocouple is located close to the sample but not touching the electrodes.

7. The thermocouple module 80TK should be set to '°C' and the Fluke75 digital multimeter to the 300mV DC range. At this stage the reading displayed should correspond to the ambient temperature.

8. Next the temperature chamber should be powered on and the temperature set to the lower limit at which the sample is to be tested (e.g. -20°C). After the chamber has attained the set temperature it is necessary to wait for about 3 - 5 minutes for the sample to attain equilibrium.

9. Now, the grounding from the HV bushing of the potential transformer should be removed and voltage applied to the sample (starting from 0V). At the same time it is necessary to observe the oscilloscope/ PD561 for indication of partial discharges and the voltage at the point of initiation should be recorded.

10. Next, the voltage applied to the sample should be reduced to 0V power shut off and the HV bushing of the potential transformer grounded. Further the temperature should be set to the next higher value and after waiting for 3 - 5 minutes again step 9 should be repeated.

11. Steps 9 and 10 should be repeated till the maximum temperature at which the sample is to be tested has been reached.

3.2 Aging caused by Partial Discharges

Aging occurs in an insulation when it is subjected to sustained voltage and temperature stresses. Hence, the need is felt to be able to analyze the signs of aging in order to predict the stage beyond which the insulation fails. In order to achieve this an attempt is being made to study the variation of partial discharge initiation voltage with aging and the variation of charge distribution of the discharge pulses with aging. As a result the following two test strategies have been adopted.

- Aging characterized by variation in partial discharge initiation voltage.
- Aging characterized by variation in charge distribution of partial discharge pulses.

3.2.1 Aging characterization by Partial Discharge Initiation Voltage

In this method of characterization of aging the temperature is kept fixed at a certain value and the voltage is kept constant at the rated value of the sample under test. Further, the partial discharge initiation voltage is measured at regular intervals of time for a period of 3 - 5 days. This test can be performed at both high (e.g. 120°C) and low (e.g. -20°C) temperature extremes and, also over the normal operating temperature range (e.g. ambient ±20°C).

This test uses the setup shown in fig 2. in conjunction with the Tektronix 2430A digital oscilloscope or the Haefely PD561 partial discharge detector. The protocol to be followed is as follows:

1. The equipments should be setup as shown in the block diagram in fig 7.

2. Steps 2 through 9 of the protocol in section 3.1 should be followed.

3. Next, the voltage should be reduced to the rated voltage of the sample.

4. After a period of 24 hours again the voltage should be increased till partial discharges are observed and the voltage at this point noted.

5. Steps 3 and 4 should be repeated for 3 - 5 days (or more if required).

6. Further, the temperature should be increased to the next higher value and after 3 - 5 minutes the partial discharge initiation voltage measured.

7. Steps 3 to 6 should be repeated till the maximum temperature at which the sample is to be tested has been reached.

3.2.2 Aging Characterization by Charge Distribution

The temperature is maintained at a fixed value and the voltage is fixed at 10% higher than the partial discharge initiation voltage at that temperature. Then using the data acquisition and analysis system the partial discharge pulses are sampled at regular intervals of time for a period of 3 - 5 days. The pulse samples acquired are then evaluated by the ASUPD software to obtain the charge distribution. Further, the charge distributions obtained after the different intervals are compared in order to find out whether they indicate any signs of aging. This test can be performed at both extremely low temperatures and extremely high temperatures in order to study the variation in the rate of aging with temperature.

This test uses the setup shown in fig 2. alongwith the data acquisition and analysis system shown in fig 6. The protocol to be followed is as follows:

1. The equipments should be setup as shown in the block diagram in fig 8.

2. Steps 2 through 9 of the protocol in section 3.1 should be followed.

3. The voltage should be increased 10% above the initiation voltage obtained above.

4.The ASUPD software should be invoked for the acquisition of partial discharge pulse samples.

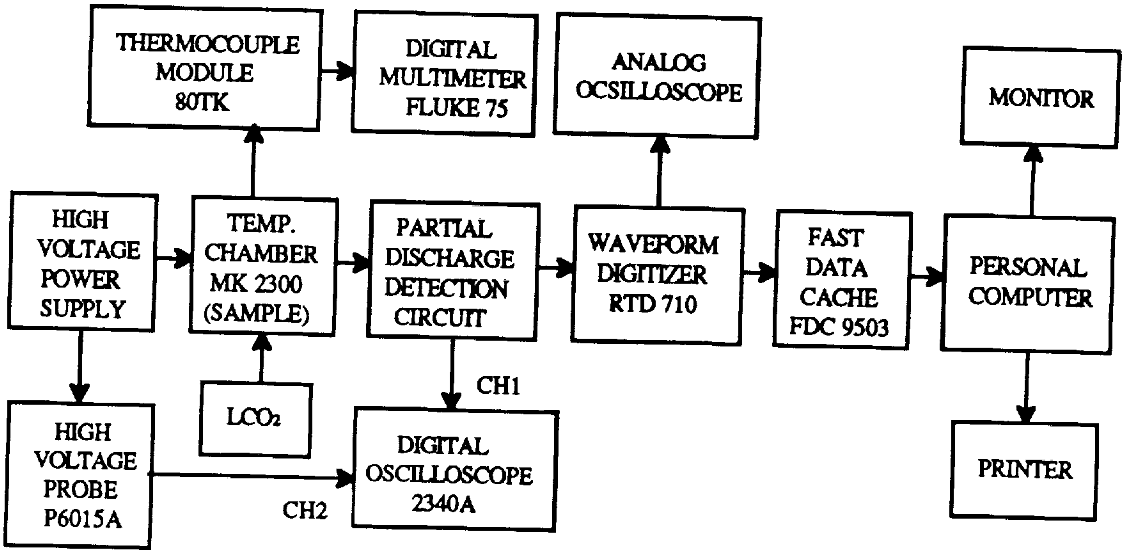

Fig 8. BLOCK DIAGRAM OF THE SETUP FOR THE STUDY OF AGING CAUSED BY PARTIAL DISCHARGES

5. Immediately after the acquisition a printout of the charge distribution of the pulses can be obtained.

6. The temperature and voltage should be kept constant at their respective values for a period of 24 hours after which another acquisition should be made by invoking the ASUPD software.

7. Step 6 should be repeated for 3 - 5 days (or more if required).

8. Next, the voltage should be reduced to zero and the temperature of the chamber increased to the next higher value.

9. After waiting for 3 - 5 minutes the voltage should be increased till partial discharges are obtained and the voltage at this point noted.

10. Steps 3 to 9 should be repeated till the maximum temperature at which the sample is to be tested has been reached.

4. Presentation of results

The setup described above was used to test commercial capacitor samples in order to study the effect of temperature on the partial discharge initiation voltage as per the protocol in section 3.1. The Fig 9. shows a typical partial discharge pulse detected using the Tektronix 2430A digital oscilloscope as the monitoring system.

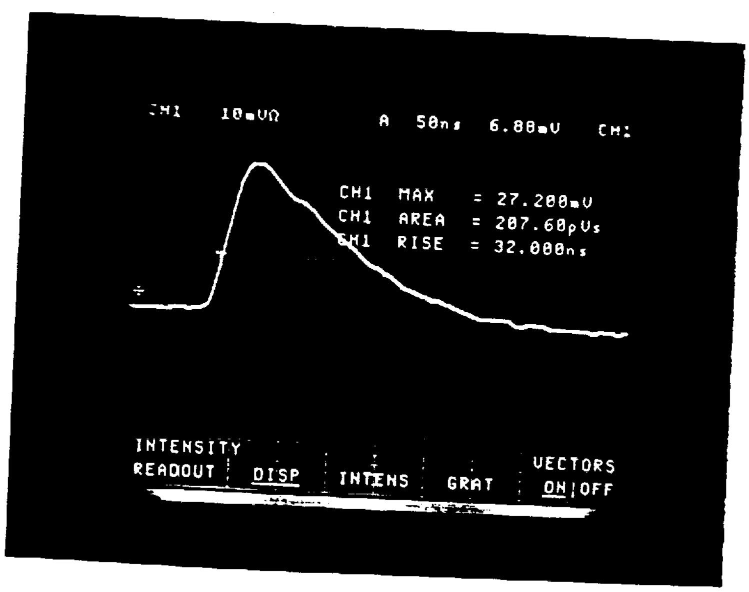

Fig 9. A TYPICAL PARTIAL DISCHARGE PULSE OBSERVED ON THE TEKTRONIX 2430A DIGITAL OSCILLOSCOPE

As mentioned in the protocol in section 3.1 the high voltage applied to the sample was monitored on the CH2 of the 2430A digital oscilloscope and the partial discharge pulses were monitored on the CH1 of the same. Also the temperature of the MK2300 temperature chamber was monitored continuously on the Fluke 75 digital multimeter. For this purpose a K-type thermocouple was used alongwith the 80TK thermocouple module. The following parameters were recorded :

1. The PD initiation voltage in KV and
2. The temperature in 'C.

For thermal equilibrium to be attained within the temperature chamber an interval of 5 minutes was allowed each time the temperature was changed to a new value.

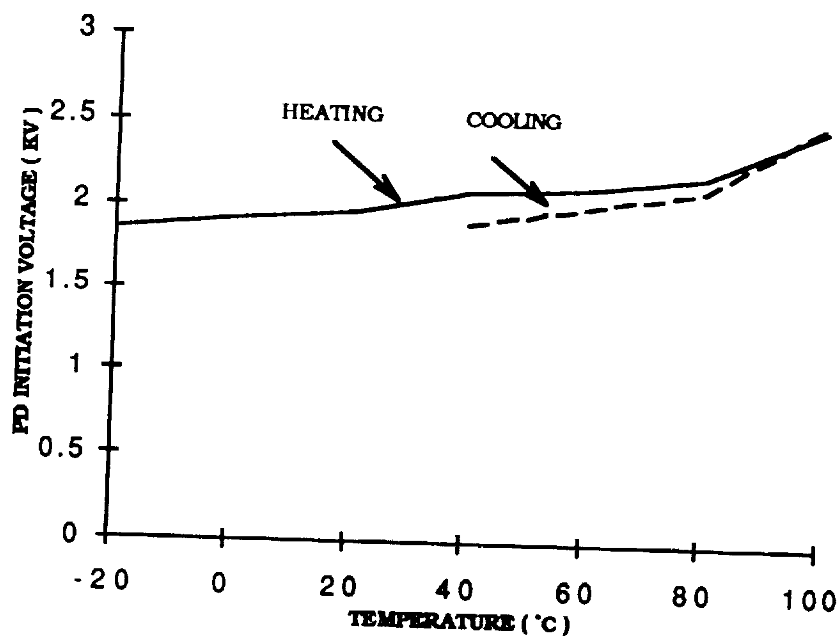

Fig 10. GRAPH OF PD INITIATION VOLTAGE VERSUS TEMPERATURE FOR 0.001μF / 3KV CERAMIC DISC CAPACITOR

The first time, the above test was carried out on a 0.001μF / 3KV ceramic disc capacitor. The sample was heated from -20°C to 100°C in steps of 20°C. During this time the PD pulses were monitored on the 2430A digital oscilloscope. After reaching the maximum temperature the sample was cooled down to 40°C in steps of 20°C but, this time the PD pulses were monitored using the PD561 partial discharge detector. The results obtained have been presented in Fig 10.

The same test was then repeated on a 0.0033μF / 1.6KV radial polystyrene film capacitor and the temperature was varied from -20°C to 100°C in steps of 10°C. The results are presented in Fig 11.

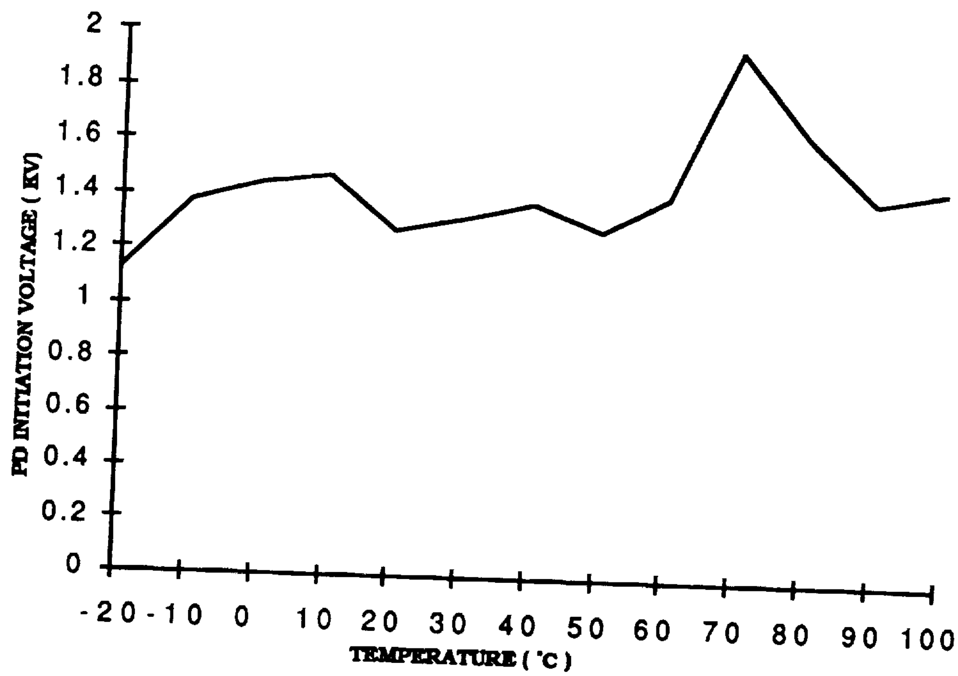

Fig11. GRAPH OF PD INITIATION VOLTAGE VERSUS TEMPERATURE FOR 0.0033μF / 1.6 KV RADIAL POLYSTYRENE CAPACITOR

Other types of capacitor samples tested using this method were plastic capacitors, one rated at 0.1μF / 1KV and the second 0.012μF / 1.6KV.

The first sample failed at 50°C and the results obtained for it are shown in Fig 12.

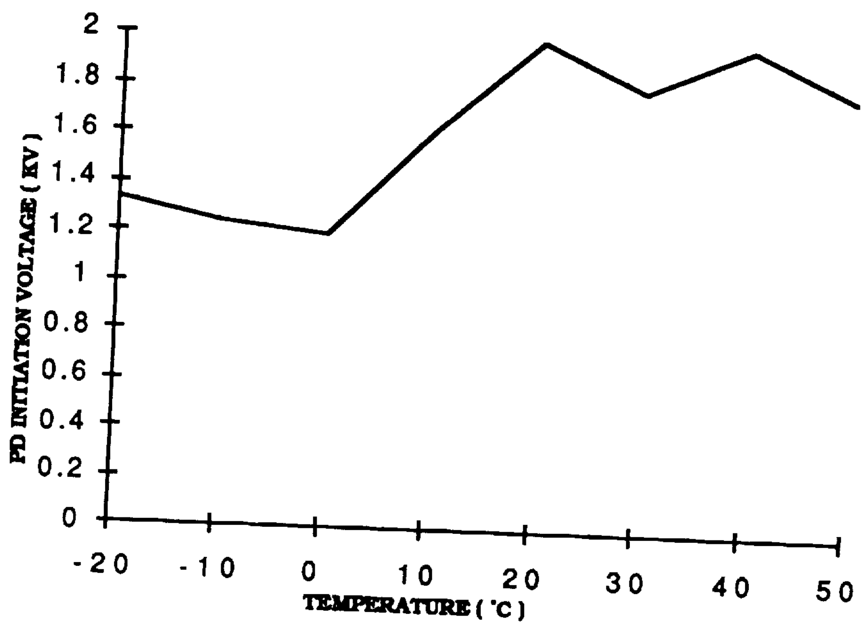

Fig 12. GRAPH OF PD INITIATION VOLTAGE VERSUS TEMPERATURE FOR 0.1μF / 1KV PLASTIC CAPACITOR

The second plastic capacitor sample rated at 0.012μF / 1.6KV was tested by heating it from -20°C to 100°C in steps of 20°C and, after reaching the maximum temperature it was then cooled down in steps of 20°C. The initiation voltage obtained at all the points were noted and the plotted results are shown in Fig 13.

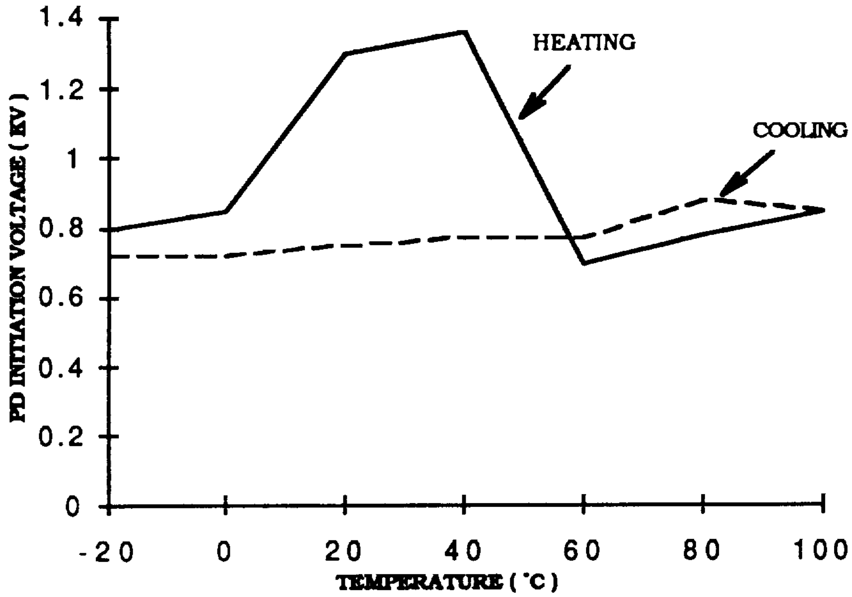

Fig 13. GRAPH OF PD INITIATION VOLATGE VERSUS TEMPERATURE FOR 0.012μF / 1.6 KV PLASTIC CAPACITOR

A second 0.05μF / 0.5 KV ceramic disc capacitor sample was tested by heating it from -20°C to 100°C in steps of 20°C. After reaching the maximum temperature the sample was cooled down in steps of 20°C. The PD initiation voltage was measured at each of these points and the results are presented in Fig 14.

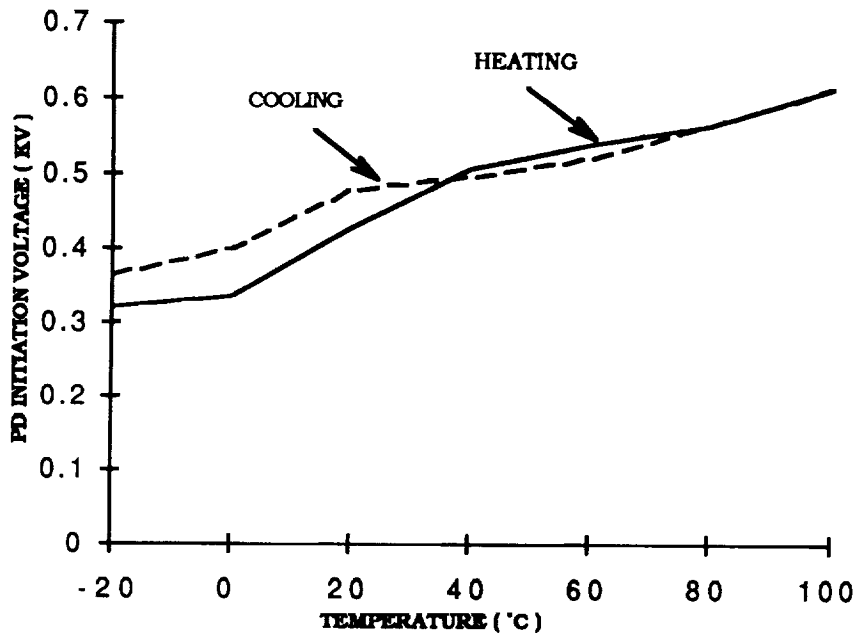

Fig 14. GRAPH OF PD INITIATION VOLTAGE VERSUS TEMPERATURE FOR 0.05μF / 0.5KV CERAMIC DISC CAPACITOR

As per the test protocol in section 3.1 the two samples provided by NASA were also tested.

The results obtained for the sample SM047A103K, 0.01μF / 0.5 KV COG Ceramic dielectric are presented in the Fig 15. The second sample SM047C224K, 0.22μF / 0.5KV X7R Ceramic dielectric capacitor showed very little signs of partial discharges but failed abruptly at 0.75KV, 20°C.

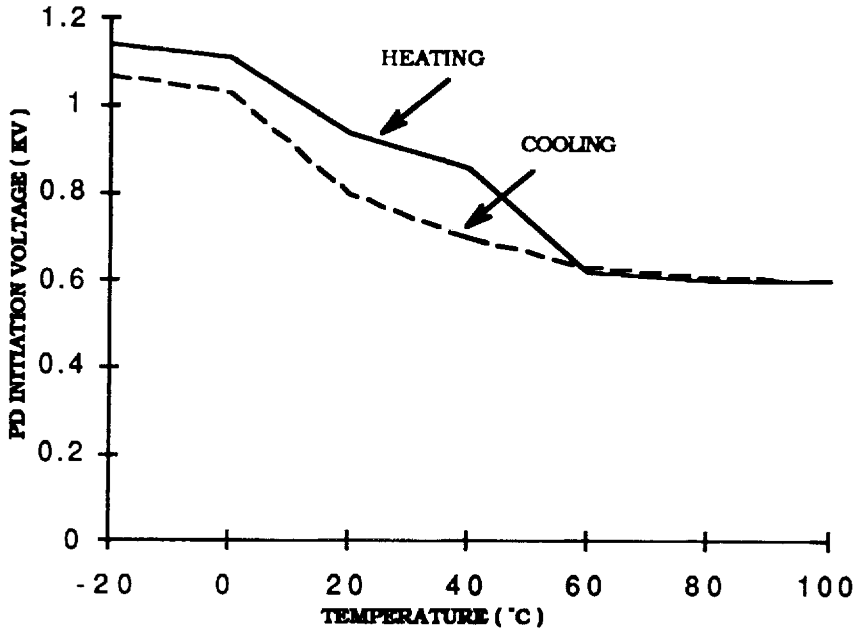

Fig 15. GRAPH OF PD INITIATION VOLTAGE VERSUS TEMPERATURE FOR SM047A103K, 0.01μF / 0.5KV COG CERAMIC DIELECTRIC

4.1 Discussion of Results

All the tests carried out using the commercial capacitors indicated an increase in the partial discharge initiation voltage with temperature. The failure of one of the plastic capacitors and, a steep decrease in the initiation voltage in the second indicates that these types of capacitors are not suited for applications where the surrounding temperature may increase beyond about 40°C.

The results obtained with the SM047A103K, 0.01μF / 0.5KV COG Ceramic dielectric indicate that the PD initiation voltage decreases from nearly 110% above the rated voltage at -20°C to 20% above the rated voltage at 100°C. This clearly implies a very reliable performance at the rated voltage even under widely varying operating temperature conditions. At this point, no comments are being made about the SM047C224K, 0.22μF / 0.5KV X7R Ceramic dielectric capacitor until further tests like, for example, the aging tests mentioned in section 3.2 are carried out.

5. Conclusions

The increase in PD initiation voltage with temperature in commercial capacitor samples can be attributed to the fact that with an increase in temperature the dielectric used in the capacitor expands and so do the voids within them. Consequently, a higher voltage is required to cause discharges in the enlarged voids. Also it is clearly noticeable that the initiation voltage is equal to or less than the rated voltage of the samples.

However, the decrease in the PD initiation voltage with increasing temperature in the COG ceramic dielectric sample contradicts the above reasoning. Since the PD initiation voltage is greater than the rated voltage of the capacitor throughout the testing range, it indicates that the capacitor will operate reliably.

6. Future Work

Since contradictory results have been obtained using commercial capacitors and those supplied by NASA, it is necessary to run similar tests on a number of samples of the same type to justify that the trend followed in all of them is indeed the same. This would also enable the prediction of the performance of the sample under given conditions.

Also it remains to be seen how well the aging of a sample can be predicted based on changes in the PD initiation voltage and charge distribution.